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Creating a circular EV battery value chain: End-of-life strategies and future perspective

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ABSTRACT

The rapid uptake of electric vehicles (EVs) will be vital to decarbonise the transport sector and achieve climate change targets. However, this transition is leading to an increased demand for key battery materials and associated resource challenges and supply-chain risks. On the other hand, discarded EV batteries create business opportunities for second life and recycling. This study presents scenario-driven material flow analysis (MFA) to estimate the future volume of EV battery wastes to be potentially generated in Sweden and future demand for key battery materials, considering potential EV fleet, battery chemistry developments, and end-of-life strategies of EV batteries. Further, we combine MFA with a socio-technical approach to explore how different socio-technical developments will affect both EV battery flows and the underlying systems in the future. Recycling has the potential to reduce primary demand by 25–64% during 2040–2050 based on projected demand, meaning that waste streams could cover a considerable part of the future raw material demands. Second-use of EV batteries can promote circularity yet postpones recycling potentials. From a transition perspective, promoting recycling, second-life use of EV batteries and advanced battery technologies entail system disruption and transformational changes in technology, markets, business models, policy, and infrastructure and user practices. Demand for high-capacity batteries for grid decarbonisation and aviation applications may contribute to the emergence of niche battery technologies. Each scenario highlights the need for effective policy frameworks to foster a circular EV battery value chain.

1. Introduction

The decarbonisation of the road transport sector is an essential part of achieving global and national net-zero targets in line with the goals of the Paris Agreement. A potential solution for avoiding the negative impacts of climate change is the transition to electric vehicles (EVs), considering their ability to reduce energy consumption and emissions. The climate benefit of EVs, coupled with technological progress and continuous policy and business support, has led to increased EV sales globally, exceeding 10 million in 2020 (IEA, 2021). It is projected that nearly 230 million EVs will be circulating globally by 2030, according to the International Energy Agency's (IEA) Sustainable Development Scenario (IEA, 2021).

The forecast growth in EV deployment is expected to increase demand for batteries. At present, lithium-ion batteries (LIBs) such as lithium nickel manganese cobalt oxides (NMC) and lithium nickel cobalt aluminium oxide (NCA), are the most common type of battery used in light-duty commercial and passenger EVs (Tsiropoulos et al., 2018). The projected rise in EV batteries however has raised concerns over the sustainable supply of battery materials. There are supply risks associated with the geopolitical concentrations of the battery elements and concerns regarding the future of the raw material supply availability, such as for cobalt and natural graphite (van den Brink et al., 2020). Moreover, there are social and environmental issues associated with mining of materials (Banza Lubaba Nkulu et al., 2018), lack of adequate information on the environmental impact of mining and upgrading activities

Abbreviations: BEV, Battery electric vehicle; EV, Electric vehicle; EOL, End-of-life; ESS, Energy storage system; ICEV, Internal combustion engine vehicle; LIB, Lithium-ion battery; MFA, Material flow analysis; MLP, Multi-level perspective; NCA, Lithium nickel cobalt aluminium oxide; NMC, Lithium nickel manganese cobalt oxide; PHEV, Plug-in hybrid electric vehicle.

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(Rajaeifar et al., 2022) and significant consumption of fossil-based energy in the upstream processes (Kelly et al., 2019). Another supply chain challenge is the uncertainty in the battery material demand estimations since EVs and LIBs are both emerging markets, and there is variability in the battery chemistry, EV adoption estimations, and other battery application parameters (Rajaeifar et al., 2022).

Management of waste batteries is of significant importance and has increasingly gained attention in research. Study on the expected future development of the EV battery waste stream may guide process developments, investment and expansion plans for recycling and second use infrastructures (Abdelbaky et al., 2021). Furthermore, understanding of current and future EV battery demand and waste stream is necessary to help make informed decisions on policy and strategic decisions in the industry, as well as to evaluate potential supply risks, social and environmental impacts of developing an entire value chain for batteries (Xu et al., 2020). A number of strategies can be explored to effectively reduce demand for new batteries in EVs and other applications, in line with circular economy (CE) principles.

Previous studies have focused on estimating the future demand for EV battery materials at the global level (Baars et al., 2021; Xu et al., 2020) as well as regional levels such as Europe (Abdelbaky et al., 2021) and the United States (Richa et al., 2014; Shafique et al., 2022) using material flow analysis (MFA). Due to the dynamic nature of the EV market at a national level, previous works also estimated stocks and flows of EV batteries and/or the future demand for raw battery materials in different countries, such as China (Liu et al., 2021; Shafique et al., 2022), Norway (Thorne et al., 2021), UK (Kamran et al., 2021), Ireland (Fallah et al., 2021) and Brazil (Duarte Castro et al., 2021). These studies highlighted resource challenges across the supply chain, particularly lithium and cobalt, in the short term and demonstrated the importance and potential contribution of EV battery recycling to fulfilling the material needs of producing EV batteries. For instance, Baars et al. (2021) found that new battery technologies will provide the most promising strategies to reduce the dependency on cobalt considerably but could result in burden-shifting, such as an increase in nickel demand. Abdelbaky et al. (2021) showed that the future waste stream is subject to a high uncertainty related to evolving material composition of batteries, possible commercialisation of cobalt-free battery technologies and battery lifetime.

Most prior studies in the waste management field however have a limited focus on socio-technical aspect, specifically less discussion on supportive enabling reforms in creating a circular EV battery value chain. Sociotechnical approaches may play important roles in research associated with waste management and represent a research gap to be filled (Andersson et al., 2019). Complementary perspectives dealing with policy domain, country-specific industry challenges, attitudes and behaviours towards waste management are relevant in order to uncover ways to address resource issues and further develop waste management industries (Andersson et al., 2019). Hence, both quantitative estimation of battery material demand and qualitative studies of potential transition toward circular EV battery are worth exploring. Here, we go beyond previous studies by combining MFA with a socio-technical approach to explore both material and social dimensions, i.e. how different socio-technical developments will affect both EV battery flows and the underlying systems, particularly the electric mobility and waste system, in the future.

Empirically, the paper is based on a case study in Sweden. Sweden is one of the leading countries in electric mobility and amongst countries with the highest market shares of EVs globally (IEA, 2018a). Hence, it is expected that a significant amount of battery waste will be generated in the next few years in Sweden, giving opportunities for recycling and second use applications. To the authors' knowledge, no comprehensive studies have yet quantified the prospective volumes of spent LIBs in Sweden and the associated future demand for battery materials (Melin, 2019). Tadaros et al. (2022) have analysed input, and optimised a future supply chain for spent LIB in Sweden. However, the model focuses on optimisation of location facilities and provides no estimation on future demand for EV battery raw material and discussion on the enabling environment to make the sustainable EV battery value chain feasible. Responding to this, the objective of this research is twofold, first to estimate the volume of electric passenger vehicle batteries projected to enter the waste stream, and material demands for EV batteries in the near and long term future, as well as investigate recycling and reuse opportunities in Sweden. The second objective is to draw attention to the complexity of socio-technical processes by embedding the scenario in the overall socio-technical transitions towards a CE of EV batteries and discussing challenges associated with transitions. Incorporating socio-technical aspects may provide insight into the supportive enabling policy reforms that would facilitate the creation of a circular battery value chain and contribute to envisioning and coordination of policy efforts.

Sweden has set a national target to decrease emissions from domestic transport by at least 70% by 2030 (Government Offices of Sweden, 2018) and proposed a mandatory target to ban new internal combustion engine (ICE) car sales by 2030. Given the clear decarbonisation goals, resilient power grid along with policy instruments that promote transport electrification have significantly influenced EVs adoption in Sweden. In terms of developing sustainable battery production, Sweden also has a strong position, with access to raw materials, cheap and low carbon electricity, expertise as well as key actors along the entire value chain, from mining, battery production, recycling, and application in the automotive and energy sectors (Fossil Free Sweden, 2020). These all make the country an interesting case to analyse.

Currently, recycling infrastructure of EV LIBs in Sweden has not yet fully developed, mainly due to the current insignificant volumes streams of end-of-life (EOL) LIBs. In terms of local recycling activities, the Swedish battery manufacturer Northvolt through its Revolt pilot project currently has a recycling capacity of 100 tons per year adjacent to Northvolt Ett gigafactory in Skellefteå, Sweden, handling NMC and NCA lithium-ion chemistries. In Sweden, the second-life use of EV LIBs has been applied in pilot trials while only a few commercial energy storage applications exist globally. Given the importance of designing future recycling and reuse infrastructure and supply chain network, studying the expected future development of the EV battery waste stream and its EOL strategies is crucial.

We structure our paper as follows: in Section 2, we present the methodology and analytical framework. Section 3 discusses the impact of different EOL strategies for EV LIBs on the projected volume of batteries and materials demand, and further analyses each scenario through the lens of socio-technical theory. Section 4 discusses current and future perspectives on the circular economy of EV batteries in Sweden and EU. Finally, we draw some general conclusions, summarise the implications for practice and offer recommendations for further research.

2. Materials and methods

Our research design comprised three parts: (i) scenario development, (ii) quantitative flow analysis (MFA), and (iii) socio-technical transition analysis. MFA is a well-established quantitative method for investigating material stocks and flow, allowing a quantitative estimation of the overall net demand for battery materials. In conducting MFA, the level of uncertainties about the future trend of EVs and battery technologies makes the EOL estimation highly challenging. This paper addresses these uncertainties in EOL battery stock estimation and future materials demand by (i) modelling the EV market diffusion based on government policy proposal (ii) scenario based analysis considering potential EV fleet, battery chemistry developments, and EOL strategies of EV batteries.

To achieve the second objective of this paper, a review of the existing literature on management of EV batteries in Sweden, and where relevant in Europe, was conducted by adopting socio-technical system perspectives. The sociotechnical perspective not only accounts for technological aspects, but also institutional, policy and regulatory frameworks as well as economic aspects. Research studies in published peer-reviewed journals focusing on battery waste management were searched for in several databases and search engines (e.g. Scopus, Science Direct, Web of Science). The grey literature such as government publications, company and institution reports, dissertations/theses and policies documents is also included to cover niche topics (Swedish perspectives) and increase the reviews' comprehensiveness (See Table A1 in the Supplementary Material for the list of reviewed papers). The qualitative aspects of the study allowed us to provide richer and more detailed insights on how to achieve circular economy approaches.

2.1. Material flow analysis

2.1.1. Model overview

We used MFA to analyse stocks and flows of materials for EV batteries. The MFA model estimates the current and future material demand for EV batteries and EOL materials available for recycling or second use. Modelling and flow calculations are performed in Microsoft Excel. An overview of the model and analysis linkage is shown in Fig. 1. It comprises two main parts: vehicle fleet model and material flow model.

First, the Swedish vehicle fleet and future EV fleet development until 2050 is modelled based on historical and statistical data of Swedish vehicle sales, scenario assumptions (i.e. EV adoption dynamics) and assumed characteristics for the Swedish fleet. The EV stock then determines the battery stock, including the battery inflows and the outflow of EOL batteries. To analyse the flow of battery materials, battery characteristics (battery capacity, size and chemistry), expected future battery chemistry development, and market shares are incorporated in the MFA model. The model and parameters are described further in the following subsection (2.1.2 - 2.1.3), and more detail can be found in the Supplementary Material. Four circular economy scenarios, adapted from Baars et al. (2021), are modelled considering five parameters: battery collection rate, percentage of batteries replaced before the end-of-life vehicle (ELV), second use rate, material recovery rate and rate of adoption of new battery chemistries (Table 1).

2.1.2. Vehicle fleet evolution

The vehicle fleet model tracks the evolution of the passenger car fleet in Sweden. Passenger cars account for over 80% of the total traffic mileage on Swedish roads (Swedish Transport Administration, 2019) and represent the key segment with regards to the current number of batteries placed on the market (Dahllöf et al., 2019), indicating that the battery electric vehicles (BEV) passenger cars will drive the majority of battery demand in the near future.

We adopted a similar approach to Morfeldt et al. (2021) in generating a stock of different powertrains (internal combustion engine vehicle (ICEV), (plug-in hybrid EVs) PHEV and BEV) that matches the current Swedish passenger fleet. The model was initiated in 1950 and then estimates the evolution of the Swedish vehicle fleet until 2020, taking into account the historic data sales and the expected vehicle lifetime. The historical data on past vehicle registrations of ICEV, PHEV and BEV in Sweden between 1950 and 2020 is collected from BIL Sweden (BIL Sweden, 2021) and Trafik Analys (Transport Analysis, 2021). The model then estimates the future EV fleet until 2050, depending on scenario assumptions and assumed characteristics for the Swedish fleet. More explanation of the model and the selected model parameters and assumptions can be found in the Supplementary Material (Supplementary methods and tables).

As already mentioned, the Swedish government plans to ban all diesel and petrol car sales from 2030 to lower CO_2 emissions. The European Union (EU) also plans to phase out the production and sales of

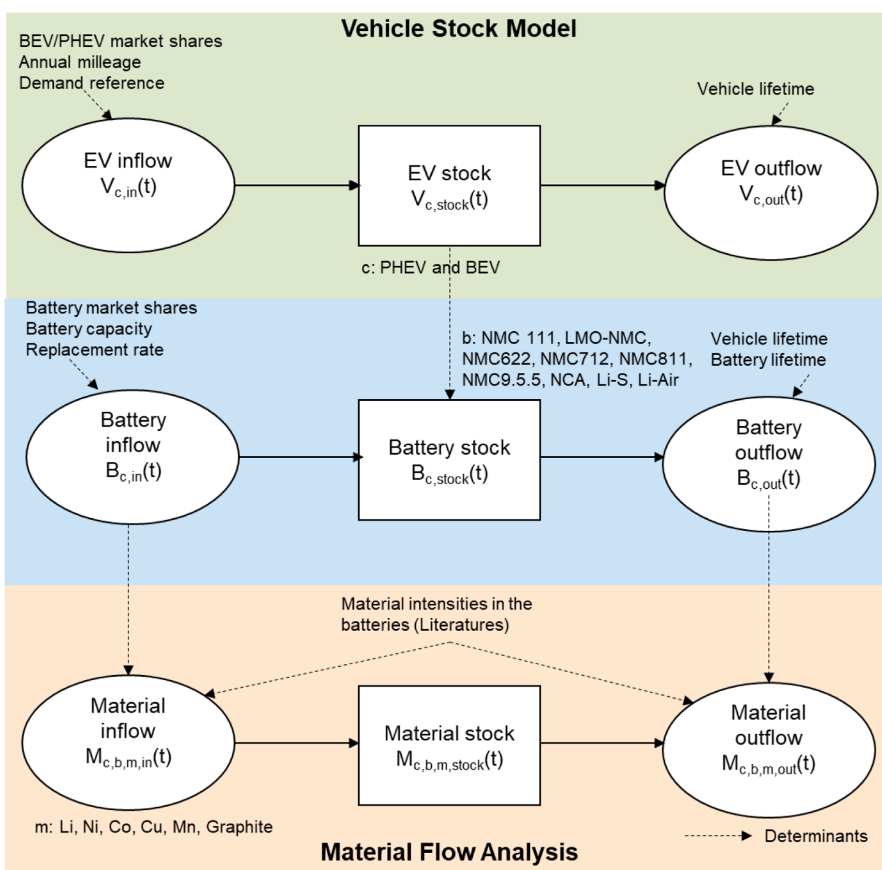

Fig. 1. Conceptual outline of the stock dynamics model. Dashed lines represent influences between variables. Abbreviations: V, B, and M = EV, battery, and material; c, b, and m = EV types, battery types, and material; in and out = inflow and outflow; t = running year. Adapted from (Xu et al., 2020).

Table 1
Overview of scenarios and assumptions. Adapted from Baars et al. (2021).

Scenario	Reference (REF)	Robust policy fostering recycling (REC)	Innovative business models fostering a sustainable battery reuse (REU)	Breakthrough battery technologies (BBT)
Description	Electric vehicle sales continue to rise along with the ban on the sale of new petrol and diesel cars from 2030, but no substantial improvement from the EOL handling in 2018 leading to loss of valuable resources	More stringent policy-driven recycling framework leading to a higher EV battery collection and recycling rates	Innovative business models lead to increased EV-battery leasing, such that the automotive original equipment manufacturer (OEM) or battery OEM can maintain ownership of the battery's second revenue stream. Batteries are replaced after 8 years, resulting in a large amount of batteries for second-life applications	Breakthrough technologies (Li-S and Li-Air batteries) enter the market in 2030, which can significantly reduce nickel and cobalt dependence
Input				
Battery collection rate	The collection rate remained at ~61%, similar to the 2018 level based on national data (Naturvårdsverket, 2020)	100% by 2025	The collection rate was set to grow from ~61% at present based on national data to 85% by 2030 following EU target (European Commission, 2016) and 95% by 2050 (The Advanced Rechargeable and Lithium Batteries Association, 2018)	The collection rate was set to grow from ~61% at present based on national data to 85% by 2030 following EU target (European Commission, 2016) and 95% by 2050 (The Advanced Rechargeable and Lithium Batteries Association, 2018)
Batteries replaced before end-of-life vehicle	Low (5%)	Low (5%)	High (95%)	Low (5%)
Second use[a]	No, directly to recycling	No, directly to recycling	50% remanufactured, 50% repurposed in energy storage system	No, directly to recycling
Recovery rate	95% for cobalt, nickel, manganese and copper, while lithium and graphite are not recovered.	99% for cobalt, nickel, manganese and copper, and 95% for lithium and graphite	95% for cobalt, nickel, manganese and copper, and 70% for lithium and graphite	95% for cobalt, nickel, manganese and copper, and 70% for lithium and graphite
Future battery chemistry	High-nickel chemistries scenario (see subsection on battery chemistries)	High-nickel chemistries scenario	High-nickel chemistries scenario	Li-S and Li-Air scenario
Socio-technical analysis[b]	Business as usual, based on current policy and moderate advances in technology	Policy and regulation driving technical changes and the development of innovation towards CE in battery technology	New business models by both incumbents and smaller, innovative firms driving change	R&D breakthroughs in new technologies
Level		Landscape	Regime	Niche
Context		Government initiative	Actors re-orientate towards new business models	R&D and pilot projects

[a] Repurposing can be defined as the process of transforming used EV batteries to fit another application (e.g. energy storage system or ESS), unlike remanufacturing where it is reused in the same application.
[b] Scenario REC can be characterised as a process mainly on the landscape level, REU mainly on the regime level, BBT on the niche level.

ICEVs by 2035. Thus, in this study, the forecast of EV sales is mainly influenced by government goals and regulatory proposals. All base scenarios adopt the implementation of a sales ban on ICEVs from 2030, by assuming the share of chargeable cars to increase linearly to 100% by 2030 from 32.2% in 2020 and the share of BEVs in chargeable cars grow from 30% in 2020 to 100% by 2030. The phase-out proposal does not specify if PHEVs would be included in the goal. However, the recent incentive policy change to re-weighting the incentive between PHEVs and BEVs, resulting in BEVs getting relatively more attractive, indicates greater support toward BEVs.

2.1.3. EV battery technologies – battery compositions

The annual inflow of EV batteries is estimated from projected EV sales and battery replacement rates associated with each scenario. The annual outflow of batteries is determined based on battery and vehicle lifespans. In the final stage of modelling, the specific materials contained in the battery are taken into account. The materials in a battery are estimated based on average battery capacity, battery chemistries and material compositions.

- Battery capacity

Estimation of average battery capacity used in sold EV models was performed based on historical and statistical data of Swedish vehicle sales (BIL Sweden, 2021), and their associated battery characteristics that have been compiled in a previous study by Baars et al. (2021). The expected future battery capacity assumed in this study is 75 kWh by 2030 according to IEA projection (IEA, 2020) which assumes that the average passenger BEV battery capacity will increase to 70–80 kWh by 2030. From 2030 onwards, the average battery capacity is presumed constant since no other substantiated projections are available. Future battery capacity for PHEV models increases to 15 kWh by 2030 (IEA, 2018b) and remains constant thereafter, as tabulated in Table A3 (Supplementary Material).

- Battery lifetime

A static battery lifetime is assumed due to the lack of real-life battery degradation data and lifetime distributions for batteries. The limited evidence so far suggests that EV batteries last the life of the vehicles (Dominish et al., 2021; Thorne et al., 2021), which is generally assumed here. However, depending on the scenario (see Table 1), some percentage of BEV batteries will be replaced after 8 years. Eight years is the proxy for current battery warranty periods given by battery manufacturers. PHEV batteries are however assumed to have the same lifetime as the vehicle since there is a lack of incentive for the replacement (Baars et al., 2021). For second life batteries, studies suggest that after the first life (8 to 10 years), batteries might be able to serve an additional 5 to over 10 years, depending on the battery applications (Casals et al., 2019; Hossain et al., 2019). Despite the lack of certainty around second-lifetime, the lifespan of second use is assumed to be 10 years (Neubauer et al., 2015).

- Battery chemistries

The cathode choice will determine the demand for battery active materials like cobalt, nickel, lithium, and manganese. Currently, NMC is the most widely adopted cathode chemistry by most EV manufacturers, and its market share is forecasted to continue to grow in the coming decades (IEA, 2018b). Responding to sustainability issues and the need for more high specific energy batteries, there are ongoing research and development and commercial activities to introduce more advanced EV batteries. Further scenarios and assumptions for battery chemistries and their market share are presented in the following subsection.

2.2. Scenario-based sensitivity analysis

We model four future scenarios to explore a range of possible outcomes from different EOL strategies and battery market development. The scenarios are then linked and embedded in the overall socio-technical transition towards a CE of EV batteries. The description and key parameters of each scenario are summarised in Table 1.

In general, CE involves, simultaneously, both forward (processes, material, assembly, distribution and consumption) and reverse (repair, recondition, remanufacture, recycle and dispose) activities. In the reverse process, following the use stage, the product is retrieved and the material follows one of three post-recovery streams: reuse, remanufacturing or recycling, before it gets transformed into a product suitable for second life application. If a product has not been used to its maximum usable capacity, not broken extensively and still fit for usage for same or different application (repurposing), it follows the ‘reuse’ stream, and goes to another user who needs it. This enables them to last as long as possible. Besides, if the product is extensively broken and repairing is expensive, but have well-functioning parts, then it follows ‘remanufacturing’ stream where the well-functioning parts are used in new product. However, if the products and parts both are extensively broken with not well-functioning parts, then the products goes for ‘recycling’ to recover the original resource/raw material from the product.

Recycling, reuse and battery chemistry scenarios adopted in this study are further explained below:

- Recycling scenario

In the reference (REF) scenario, the metal recovery rate from LIB recycling is based on current commercial recycling technologies in the EU and Sweden, assuming a hydrometallurgical process. This process involves leaching and subsequent extraction of Co, Li, Ni, and Mn metals through solvent extraction and chemical precipitation, or alternative electrolytic methods (Jena et al., 2021). In particular, these methods are better suited, especially for NCM batteries where there is a need to separate different metals. In this process, Co, Ni, Mn and Cu could be economically recovered with an efficiency of around 90–98% (Xu et al., 2020). We assume the recovery rate of 95% for Co, Ni, Mn and Cu in the REF, REU and BBT scenario (Table 1). However, Li and graphite are not recovered in the REF scenario, mainly due to its economical aspect.

In the REC scenarios, some technological improvements are expected that could make a higher recovery of Co, Ni, Mn and Cu (99% efficiency), and recovery of Li and graphite more favourable. For instance, advances in hydrometallurgical process (that also recovers high-quality graphite and lithium) or advances in efficient direct recycling process leading to improved economic and environmental benefit (Xu et al., 2020). In the direct recycling or so called cathode-to-cathode recycling, battery materials of LIBs are recovered directly after a pretreatment process as one battery-grade compound making the process potentially more economical (Jena et al., 2021). Economic improvement could also be driven by political support and financial incentives. According to a study by Yang et al. (2021), over 90% of graphite could be recovered for high-quality applications. While we assume a 95% recovery rate of lithium graphite in the REC scenario, a lower recovery rate of 70% is assumed in the REU and BBT scenarios.

Since Li-Air/S batteries are a new, innovative battery system, there are no substantial approaches for a recycling methods so far. Schwich et al. (2020) have proposed a combination of thermal treatment, mechanical treatment and hydrometallurgical processing to recycle Li-S batteries. In the BBT scenario, hydrometallurgical methods are also assumed for recycling of Li-S and Li-Air batteries.

- Reuse scenario

The potential of second-use of EOL EV batteries is also investigated which could extend the lifespan of the battery while reducing the demand for virgin materials. The amount of batteries used in second life applications is however highly uncertain depending on the battery state-of-health, battery chemistry, and the associated business cases (Xu et al., 2020). In the REU scenario, for simplification purposes and simulating the effect of second use, we assume that 50% of EOL batteries will be used in a 10-year second-life application in energy storage system (ESS) prior to recycling. The remaining batteries are assumed to be remanufactured for EV application.

- Battery chemistry

Two main battery chemistry scenarios and market share are adopted:

1. High-nickel chemistry scenarios

In this scenario, the NMC chemistry will continue to dominate the EVs sector through 2050. It is expected that in the near future NMC batteries will follow a trend towards higher Ni content, from the already common NMC-622 to future NMC-811, due to an increase in the energy density of the cell and less reliance on cobalt (Ding et al., 2019). This is also reflected in the IEA report (IEA, 2019), major battery roadmaps in several regions and commercial activities by battery manufacturers that focus on high Ni chemistries (Xu et al., 2020). In this scenario, we assume that the share of EV battery technologies sales will evolve to 40% NMC 811, 10% NCM 712, 40% NMC 622, and 10% NCA in 2030 to 90% NMC 811 and 10% NCA in 2050.

2. Li-Sulphur/Air scenarios

Technological breakthroughs in Li-metal battery chemistries, specifically, Li-Sulphur (Li-S) and Li-Air batteries are assumed to be commercially available in the next decade. With the specific energy of two to three times higher than the current LIB, Li-S/Air batteries would likely have lower cost and improved EV ranges, hence they are considered the most promising beyond Li-ion candidates (Cano et al., 2018). However, these battery technologies are still in early stages, and various technical challenges exist to be addressed to make it commercially viable, e.g., poor life cycle, practical capacity and safety issues (Tan et al., 2017). In this scenario, we assume Li-S/Air batteries enter the market in 2030 and reach a market share of 60% by 2040, while the rest of the market follows the trends towards high nickel chemistries.

- Sensitivity analysis of ban year and average battery capacity

The main scenario builds on that new sales of ICEVs will be banned after 2030. A sensitivity analysis was performed to illustrate the effect of the timing of the ban by varying the year ICEV ban: earlier ban in 2027 and delayed ban in 2040. In addition, since EV battery capacity is also key for determining the quantity of required materials, we performed a sensitivity analysis on the extreme situations, assuming large BEVs with 125 kWh capacity.

2.3. Conceptual approach: socio-technical transition and MLP

The circular economy (CE) is often referred to as a closed-loop, as opposed to the 'take-make-dispose' approach in linear economy. A CE keeps products and materials in use, regenerates natural systems, and designs out waste and pollution through business and design principles (Ellen MacArthur Foundation, 2017). Hence, the transition to a CE has promising potential to decrease resource use, thereby limiting climate and environmental impacts.

A transition towards a CE of EV battery is a multi-faceted challenge that is subjected to a range of influencing factors, including consumption trends, technological innovations, social norms and policy interventions. Transitioning from current linear models of resource management towards circular models of resource use will require insights into how socio-technical transitions may occur. Further, a transition perspective on CE allows an assessment of the capacities of different socio-technical processes, e.g., battery waste recycling, to fundamentally change the underlying systems and economic structures.

In this paper, we applied the multi-level perspective (MLP) that was first developed by Rip and Kemp (Rip and Kemp, 1998) and further refined by Geels et al. (Geels, 2002; Geels et al., 2016), as an analytical bridging between MFA scenario and socio-technical transition studies. The MLP is based on the understanding that technologies do not exist in a social vacuum but that they are context-specific depending on key socio-economic and socio-political factors that influence technical change and the diffusion of innovation. The MLP explains transitions with the interactions and interplay at three levels: niches, regimes, and landscapes (Geels, 2002). The landscape (macro-level) is considered an external context for interactions of actors (e.g. economic crisis, political development, climate change) (Geels, 2011). The regime level represents the current structures and practices characterised by dominant rules, institutions, incumbent firms and technologies that are self-reinforcing (Geels, 2011). Niches are spaces where innovative activity takes place and where protection is offered from dominant rules, for example in an research and development (R&D) context (Geels, 2011). According to the MLP, a socio-technical transition might occur if a niche is sufficiently developed, while landscape changes exert pressure that can destabilise the socio-technical regime. The resulting destabilisation of the regime then may create opportunities for niche innovations to compete with, modify or replace the regime (Geels and Schot, 2007).

Through the three-levelled dimensions (niche, regime, landscape), the MLP serve to understand system innovations and analyse actors involved and policy influenced socio-technical changes (Geels et al., 2016). We conducted desk research combining our data with theoretical insights from MLP research and empirical findings of related transition studies. Specifically, future scenarios for the landscape, regime, and niche level were elaborated using the MLP as a framework, a similar approach previously done by (Jedelhauser et al., 2018). In doing so, we analysed current policy initiatives, research project, related scientific articles and grey reports as well as current debates related to transition towards sustainable EV battery value chain (see Appendix Table A1).

Operationalizing the MLP in socio-technical analysis needs placing particular attention to understanding how the positions, objectives, preferences, resources, and interactions between actors at the regime and niche levels are changing over time (Lauttamäki and Hyysalo, 2019). In elaborating the scenarios, issues important for understanding the main driver of each scenario were first analysed in accordance with one of the three analytical levels. For the landscape level, the main important landscape factors contributing to change in the battery EOL and technology adoption were explored from literature sources, including policy documents. We also analysed tensions in the incumbent regime created by landscape pressures which can give an understanding of regime dynamics and institutional change, thus complementing the big picture of the factors shaping transitions (Geels et al., 2016; Lauttamäki and Hyysalo, 2019). When mapping change processes on the regime level, we analysed multiple dimensions such as technology, markets, infrastructure, industry structure, policy, and scientific knowledge, as elaborated by Geels (2002). For niche level, the analysis focuses on processes addressed as essential for the successful development of a technological innovation, i.e. articulation of expectations and visions, network formation, and learning processes (Lauttamäki and Hyysalo, 2019; Verbong and Geels, 2010).

3. Results and discussions

3.1. Battery flows and materials demand: the impact of different scenarios

According to the projection, for the reference scenario, the quantity of LIBs used in Swedish electric passenger light-duty vehicles is expected to increase by ten-fold in the next decade, from around 2.6 GWh in 2020 to 28 GWh in 2030 (see Fig. A2 in the Supplementary Material). This might appear as a rather extreme result due to the assumption on ICEV sales ban, however it is in line with the government policy directions. If the ban starts earlier, i.e. 2027, there's no change in the demand capacity for EV LIBs in 2030 and 2050 compared to the 2030-ban year scenario, considering both assuming BEV penetration rate of 100% from 2030 (See Fig. A3 in the Supplementary Material). For the scenario with the delayed ban, the demand for LIB decreases by half to 13.4 GWh in 2030 due to slower EV adoption rate (See Fig. A4 in the Supplementary Material).

For the REU scenario, a high percentage of early replacement results in a higher volume battery requirement leading to nearly double capacity demand in 2050 compared to the REF scenario. At the same time, repurposing EV batteries can provide around 14 GWh of storage capacity in 2050. The availability of second life LIBs could reduce the demand for purpose-built LIB storage.

Depending on the EOL strategies adopted, the number of EV batteries available for recycling changes considerably. For reference scenario, 8,600 EOL LIBs could be available for recycling in 2030. When a higher collection rate is incorporated (REC scenario), this number increases to 14,000 batteries in 2030. Considering 95% of batteries are replaced after eight years and subsequently used in remanufacturing and repurposing (REU scenario), this number decreases to 9,100 LIBs in 2030, showing a delay in recycling. The number of EOL LIBs is also affected by the timing of ICEV ban. For the same CE scenarios, there would be more EOL LIBs generated in the early ban scenario and fewer EOL LIBs in the delayed ban scenario, which is more pronounced between 2030 and 2045, mainly due to the difference in the EV adoption rate.

By assuming the average mass of EV LIB for NMC-batteries and Li-Air/S batteries (Table A3, Supplementary Material), the quantities of EOL EV LIBs that are collected and either sent to recycling or second-life application is presented in Fig. 2. As can be seen, the growth of EOL EV LIB flattens when approaching 2050 since the overall light-duty EV fleet size stabilises. For the BBT scenario, the shift to Li-Air/S batteries leads to a decline in EOL LIB quantities in the later years due to the lighter mass of the battery compared to current LIB models. By 2050, recycling capacity of approximately 170,000 – 230,000 tonnes/year would be needed to handle the EOL EV LIB in Sweden. The uncertainties associated with the estimates are linked to the underlying assumptions, particularly the second-use rate as well as the average battery capacity and EV adoption rate.

The effect of timing ICEV-ban year on quantities of EOL LIBs has the same trend as the other evaluated parameter, i.e. demand capacity. For all scenarios, an earlier-ban year leads to around 10 to 30% higher spent LIBs generated, especially between 2030 and 2045. For instance, in the REF scenario, around 2,340 tonnes and 48,480 tonnes LIBs are collected for recycling in 2030 and 2040, respectively. An earlier ban year for ICEs would result in increases in the total LIBs sent to recycling, to around 2,610 tonnes and 62,280 tonnes LIBs in 2030 and 2040, respectively. On the other hand, implementing a ban in 2040 would result in lower quantities of EOL LIBs. As the EV fleet stabilizes by 2050, the variation in

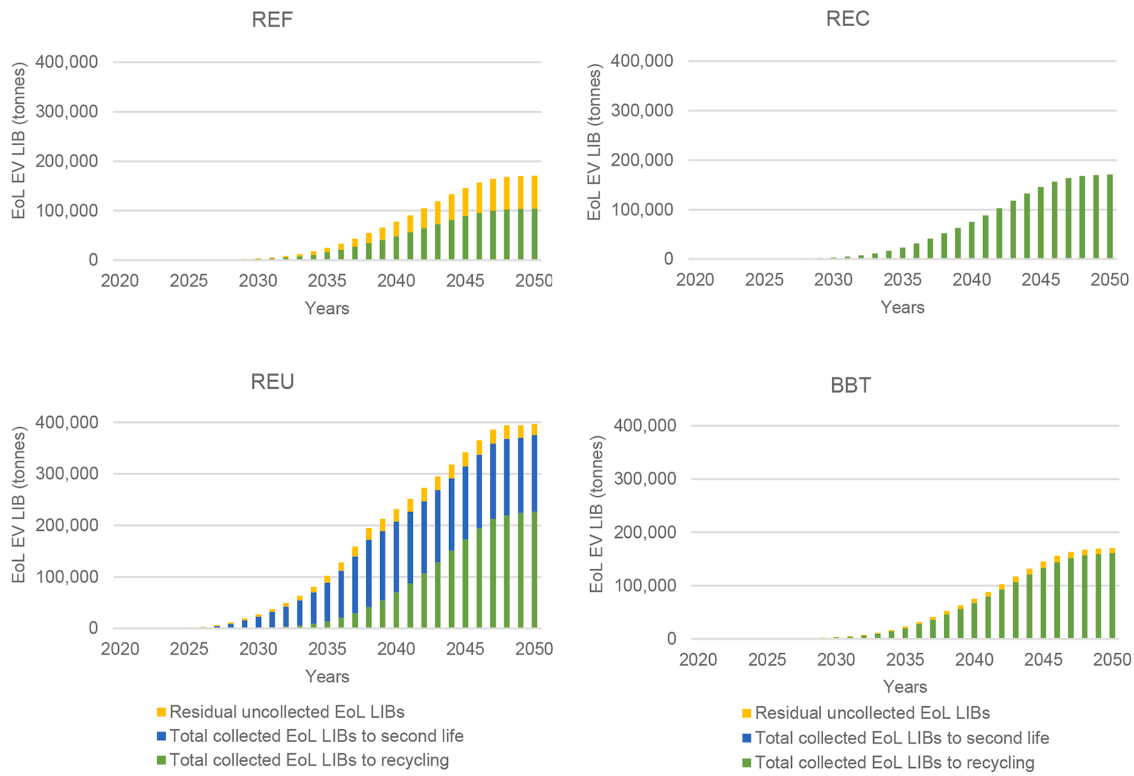

Fig. 2. Quantities of EOL EV LIBs in Sweden for different CE scenarios.

timings has no impact on the total potential of EOL LIBs generated in 2050 for the REF, REC and BBT scenarios. However, for the REU scenario, the impact of the ICEV ban year on quantities of EOL LIBs is more notable due to the assumption of high early replacement rate of EV LIBs (See Fig. A5 and A6 in the Supplementary Material).

Fig. 3 presents the results of the overall material flow analysis of the net demand for primary LIB materials in Sweden, considering the effect of recycling, second life use and future battery market share.

In the REF scenario, the demands for all materials rapidly increase until 2030, in line with the rapid increase of EV sales. The demand for Ni and Cu peaks in the early 2035s at around 20,000 tonnes/year, while Co and Mn reach their peaks in the early 2030s at around 3,800 tonnes/year. The demand for Li and graphite continues to increase towards 2050, since these materials are not recovered in the REF scenario. Recycling collected batteries results in a slower increase in the net demand between 2030 and 2035 for Ni and Cu and a net decrease from 2030 onwards for Co and Mn. Currently, it is not cost-effective to recover lithium and graphite compared with primary supplies (Moradi and Botte, 2016). The proposed regulation however envisages specific material recovery targets for Li, which is 35% by 2025 and 70% by 2030, along with increasing targets for Co, Cu, and Ni (Halleux, 2021).

Compared to the REF scenario, the REC scenario highlights the advantage of increasing the collection rate for EOL EVB, from 61% in 2020 to 100% in 2050, and recycling rate to reduce the demand for primary LIB materials. It can be seen from Fig. 3 that from the early 2030s onwards, the first large volume of EVs reaches the end of life, resulting in a substantial return flow of secondary materials (obtained from recycling) to the system, which further reduces primary materials from 2035 onwards. The result also shows that the total cumulative demand for primary Ni and Cu between 2020 – 2050 can be decreased by 22%, Li and graphite by 40% and around 29% for Co compared with the reference scenario. The negative values of primary demand indicate a surplus recycled material compared to material demands, however, this cannot be expected to continue indefinitely.

The REU scenario represents quite an extreme second-use technology adoption rate. EV manufacturers adopt circular business models based on product-service systems in this scenario. Due to early replacement of batteries, most EVs need at least two batteries over their lifetime, leading to a significant increase in materials demand, as shown in Fig. 3 REU. The materials demand is likely to peak in the 2038 and decline thereafter. It can be observed that higher early replacement in the REU scenario leads to 1.3 times higher annual material demand than in the REF scenario in 2040. In the REU scenario, primary demand is also greatly reduced, especially after 2040s assuming the presence of a robust recycling system. A large amount of used EV batteries with residual capacity could be potentially reused in EV applications (through repair and remanufacturing) or repurposed in ESS.

The BBT scenario assumes a breakthrough in new battery technology developments. These technological improvements would in turn shape both the battery recycling and the second-life batteries markets. As a result of the full commercialisation of Li-S/Air battery, the total demand of primary Ni, Co, Cu and Mn could reach its peak by 2030 and decrease thereafter since Li-S/Air battery chemistries do not need these materials. Also, in this scenario, the market shares of NMC batteries are getting smaller towards 2050, resulting in lower demand for materials, especially for Ni and Co. Since Li-S and Li-Air batteries typically do not contain graphite, the demand for graphite in the Li-S/ Air scenario is also significantly lower.

Varying the assumptions on the ICEV ban shows a clear impact on net demand for primary LIB materials, which is expected since it affects the total EOL LIBs (Fig. 2). The peak materials demand is shifted towards the year of ICEV ban (See Fig. A7 and A8 in the Supplementary Material for sensitivity scenario). An earlier ban year for ICEVs would result in a higher demand growth rate in LIB materials. In contrast, introducing a delayed ban leads to a slowed demand growth for materials. Further, Fig. A8 shows that the peak demands for cobalt and manganese are lower than the 2030-ban year scenario.

EV battery capacity is also a determinant parameter in the estimation of materials demand. We assume that the EV battery capacity will remain at around 75 kWh from 2030 onwards for the base scenario. To

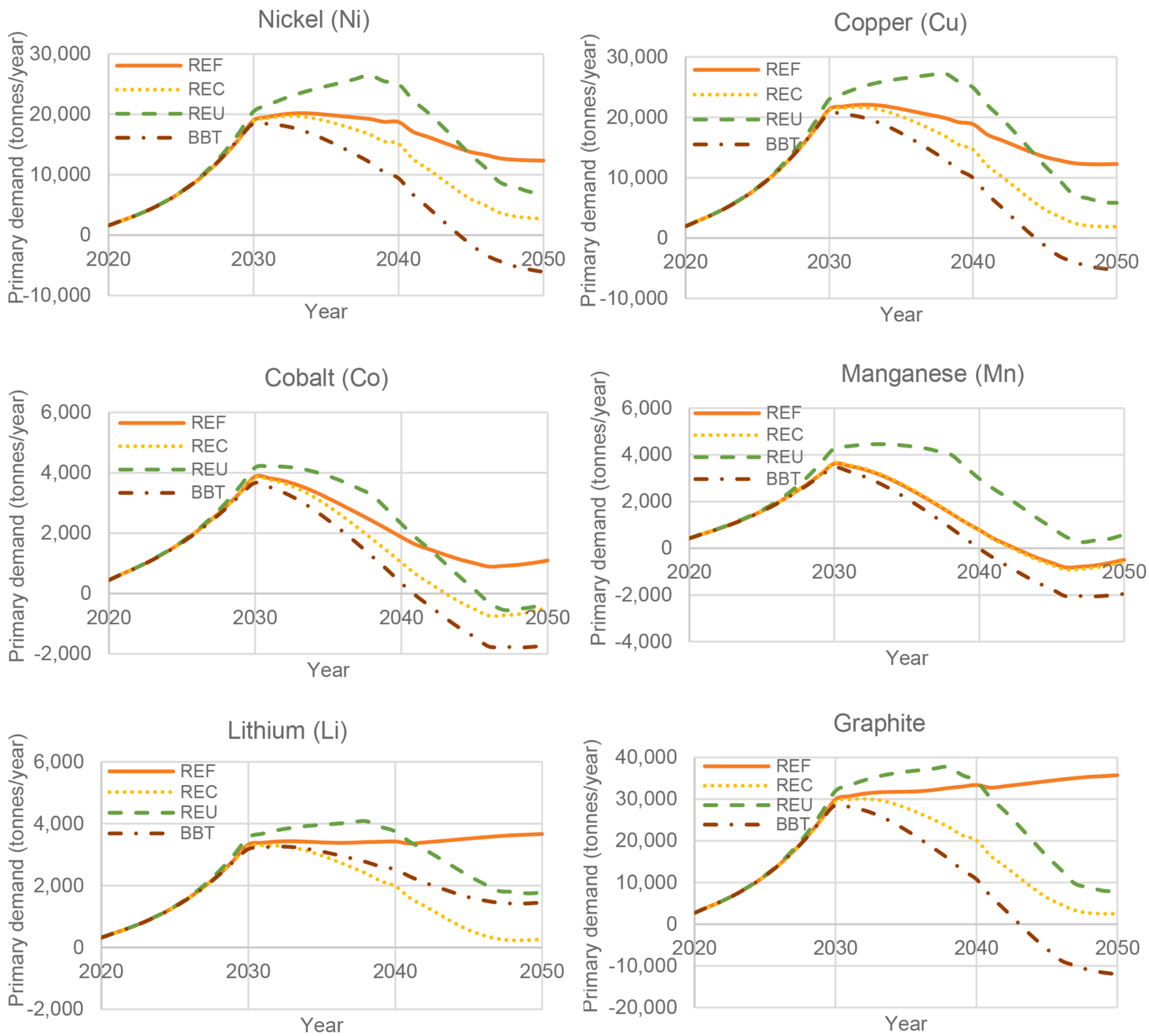

Fig. 3. Projections of net demand for primary LIB materials in Sweden, assuming the ICEV-sales ban in 2030.

explore the upper range of future material demand, we performed sensitivity analysis assuming large BEV battery capacity of 125 kWh (See Supplementary Material, Fig. A9). The result shows that the cumulative primary material demand in 2020–2050 would increase by 50 to 70%, depending on the material, due to higher average battery capacity.

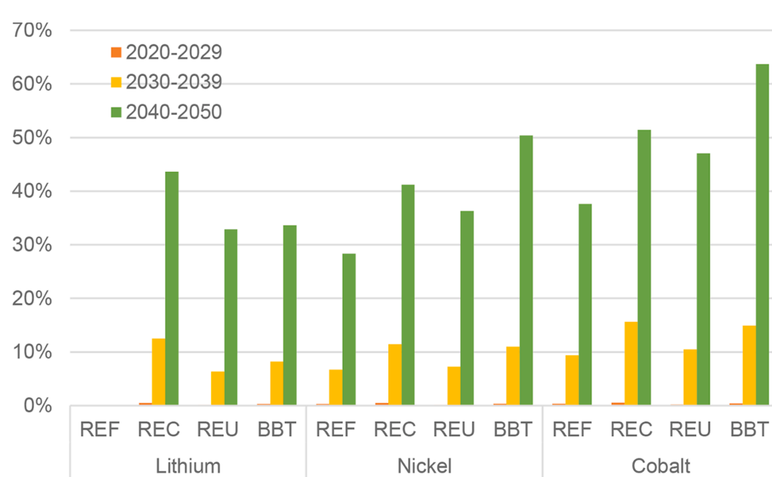

Fig. 4. Recycling potential of battery materials in periods of 2020–2029, 2030–2039, and 2040–2050.

3.2. Recycling potentials

Recycling potential (RP) is defined as the percentage of battery material demand that can be fulfilled with recycled material (Xu et al., 2020). Fig. 4 presents the temporal changes of the RP towards 2050 for different scenarios. The RP for the current period of 2020 – 2029 is very small (<1%) since the LIB volumes are still low and mainly being used in the original application. However, it may rise to 25–64% during 2040–2050. Considering complex planning to build recycling facility, the infrastructure should be in place before the battery volumes become unmanageable.

The RP for Co and Ni reach the highest in the BBT scenario (2040–2050) due to the higher stock of NCM batteries accumulated until 2030 when Li-S/Air chemistries that do not require these materials start to enter the market. In the BBT scenarios, the RP for Li metal is around 34% during 2040–2050 due to the increase growth of the Li-S/Air batteries. Instead of reusing/repurposing, direct recycling would bring some battery materials back into the value chain faster. Compared to the REC scenario, the REU scenario gives around 2–9% lower value of RPs, indicating how second life applications postpone the recycling processes.

Currently, the total LIB recycling capacity in Europe is approximately 28,500 tonnes of batteries per year (Baars et al., 2021). Considering a significant amount of EOL LIB will be generated in the next few years, there is a substantial capacity shortage in the LIB recycling capacities on the European market in general (Lunde, 2021). To achieve the recycling potential, a gradual increase of the installed recycling capacity is thus needed. The EV battery recycling market is still in its infancy mainly due to the current low volume of spent EV batteries, but some initiatives are ongoing to scale up the recycling facilities such as planned by Stena Recycling and Revolt Ett in Sweden, and by other European recycling companies or battery manufacturers.

The impact of varying timing for ICEV-sales ban also clearly influence the recycling potential, and consequently, the future recycling capacities needed. Introducing earlier ban entails the need for more advanced planning, and would highlight potential supply risks for LIB materials.

3.3. Embedding the scenarios in a multi-level transition context

Incorporating a socio-technical transition perspective can shed some light on the dynamics of transitions in socio-technical systems, particularly how transition processes on different levels might contribute to a CE of EV batteries. The analysis is presented below.

- REC scenario: The landscape level

Within the framework of the MLP, scenario REC can be characterised as a dominant process on the landscape level. There is a range of drivers operating at various spatial scales of the landscape level that are, in theory, creating the opportunity for material recovery from EV batteries and facilitating a transition in resource systems towards a CE. For instance, natural resources scarcity, climate change, waste management, regulation and economic drivers that provide incentives to push for battery recycling.

Previous scholars highlighted that the main driver in materials recycling has been legislation (Salmenperä, 2021). Thus, the narrative in the REC scenario is that the policy and regulation mainly drive technical changes and the development of innovation toward CE. At the international landscape level, the EU's waste and circular economy policy and comprehensive extended producer responsibility (EPR) schemes have put pressure on policymakers at the national landscape to act. The new EU Battery Regulation Proposal focusing on sustainability will provide stricter regulations with regards to recycling targets, collection and material recovery targets and mandatory recycled content in EV batteries, amongst others (European Commission, 2020). The government has been investing in the battery value chain, e.g. through R&D grants and created a strategy for a sustainable battery value chain. Policy instruments such as the landfill fee, EPR regulations, national waste management plans, and support for the expansion of infrastructure and advancement of material extraction technology are considered to be the key drivers in promoting the recycling.

Currently, the main limitations for scaling up EV battery recycling include low volumes, safety risks in handling, and battery composition variations (Dominish et al., 2021). The incumbent actors in the EOL sector will need to be prepared and adaptable in managing and recycling a wide range of EV battery chemistries in the near future. This requires advances in network and recycling processes and a necessity to incrementally adapt to changing battery types and sizes to economically recover various battery-grade materials. Compared to the well-established lead-acid battery industry, the lithium-ion battery industry has to be established in a relatively short time, which creates uneven development across the value chain and tensions for incumbent actors in the transition to the CE of EV batteries (Chizaryfard et al., 2022). Chizaryfard et al. (2022) further argue that the criticality of disruptions will vary amongst actors in the value chain (mining companies, material manufacturers, EV manufacturers, and recyclers), related to necessary adjustment in business models, technological expertise and operational capacity of the firms.

Legislation is one amongst many various drivers. The other possible context factors on the landscape level of a CE transition include technological (e.g., innovative battery recycling technology), economic (e.g., material prices or shortages), environmental (e.g., mining impact), political (e.g., trade agreements), social (e.g. public awareness) landscape factors could potentially influence the transition towards a CE of EV batteries.

- REU scenario: The regime level

In the REU scenario, a product–service system business model is widely adopted by EV manufacturers to create and capture value from the efficient utilisation of resources (Williams, 2007). Hence, the business model can improve the circularity of EV battery management. The business proposition for second-life applications is to potentially generate additional revenue by putting spent batteries to use in another application or selling it to a third party. Moreover, second life applications can offer economic benefits for grid storage and EV owners (e.g. alternative financial schemes) as well as provide social benefits (e.g. boost employment).

In this scenario, regime actors (automotive firms) respond to landscape pressures by reorientation towards new business models. The new business models may cover different forms of collaboration between actors along the value chain, and between large incumbents and small innovative firms. Thus, it can be considered as radical and potentially disruptive innovation to how the socio-technical system of the incumbent system works. As Bidmon and Knab (Bidmon and Knab, 2018) showed, business models can play three different roles within societal transitions: as part of the socio-technical regime, as intermediates between the technological niche and the socio-technical regime, and as non-technological niche innovation. Second life battery technologies (reuse, repurpose and remanufacture) are currently still in their niche development stage. Innovative business models may therefore facilitate these technologies to enter and disrupt the existing business model regime. The process may include gradual formation of a sub-regime that enable the second life battery technology to align to more and more actors of the current regime and then contribute to the regime's disruption from within, as illustrated by (Bidmon and Knab, 2018). For instance, the new business model or EV ownership model may disrupt the material flow (e.g. delay recycling) and the current structure of EV battery supply chain and waste management systems.

The REU scenario highlights how business models can be drivers of the CE transition. However, there are still many uncertainties regarding both technological, legal and economic aspects of second-life batteries that need to be further investigated. In the absence of deeper reforms of political (e.g. targets), regulatory (e.g. standards, incentives) and market structures, it is likely that business model innovation only will be insufficient to enact such a system change. Moreover, considering the highly institutionalised character of the battery recycling system, the implementation and up-scaling of second life applications may need to overcome existing path dependencies and socio-technical lock-ins.

- BBT scenario: The niche level

The BBT scenario sees R&D breakthroughs in new battery technologies driving changes towards CE. New advanced battery technologies such as Li-S and Li-Air (scenario BBT) are seen as niche innovations that provide alternatives to the current dominant design of NMC batteries. Li-ion batteries will likely improve incrementally, but new battery technologies may be required to achieve much higher energy and power densities. Supply constraints, the increasing need for energy storage and emerging application of batteries in niche sectors such as aviation and the maritime are driving the needs of advances in battery technology.

The advance in battery technologies may disrupt the current structure of EV battery value chain, which is complex, technology intensive, and actors is highly interdependent with other actors (Chizaryfard et al., 2022). Change in the battery chemistries have the potential to disrupt the business for mining and metals industry in terms of change in the demand for specific metals. On the other hand, the recycling firms will need to expand their technological and operational capability to handle new type of batteries.

Transitions only occur when niche innovations are robust enough to challenge the dominant socio-technical system. Niche innovations often struggle to have any impact because of the diverse technological, economic, socio-political lock-ins to dominant technological regimes. The robustness and maturity of the niche are two necessary conditions to ensure its scaling up and out, thus contributing to CE transitions. Currently, very few academic institutions or companies have demonstrated advanced batteries such as Li–S battery technology at a high technology readiness level (TRL). Further material-level developments are thus required to realise the full potential of advanced battery technology, and the academic research community has a vital role in achieving this. The battery strategies at all policy levels have also highlighted the importance of boosting research and innovation to generate a high level of knowledge to drive the niche innovations to systems change.

Considering the importance of learning processes, many European countries are engaged in promoting specialised research and innovation centres for new batteries. The engagement of actors at all levels is essential, suggesting collaboration by means of research programs, innovation networks, and the formation of industrial and research clusters. Initiatives such as the Battery 2030+, aimed at providing breakthrough science for the European battery industry, and the establishment of the Batteries Europe (European Technology and Innovation Platform), European Battery Alliance (EBA) are good examples. EBA has been promoting industrial partnerships along the value chain that are increasingly needed to mobilise public funding to trigger investment decisions.

Shifts towards Li-S and Li-Air batteries or other low-cobalt chemistries may make recycling of current key metals economically unattractive. Lithium recovery can become an attractive prospect, but for the current situation where economic drivers are absent, policy intervention may be required to incentivise recycling of the materials. Additionally, niche policies related to energy, tax, and waste related regulation will be important to address various barriers to the adoption of new battery technology. This may include formulation of long-term goals and roadmap, the creation of an actor-network, coordination of actions and strategies and, where needed, the use of subsidies, public procurement and standards.

4. Perspective on circular economy for EV batteries

4.1. EV battery value chain in Sweden

Despite huge resource and market potential of EV battery in Europe, Asian companies are dominating the global electric-battery market. Chinese and Japanese companies account for 75% of production of battery cells and 60 - 90% of the production of active materials used in batteries. Europe has therefore set targets to be an independent lithium-ion battery supply by 2025 through establishing strategic research agenda, new regulatory framework and considerable investments along the entire battery value chain. Currently, Europe has no Li-refining capacity yet, but the first lithium refinery in Europe is to be developed in Germany.

Sweden has a great potential to develop a strong position in the future European battery market with key actors in all parts of the value chain, as can be seen in Table 2. Compared to the upper value chain (production of raw and active materials), the cell production, production of packages, use and recycling are parts of the value chain that are most well established now. Table 2 also summarises the current status of

Table 2
Value chain analysis of EV battery production in Sweden. Adapted from Business Sweden (2021).

Value chain segment	Description	Key industrial actors
Raw materials	There are mining deposits relevant for battery production (lithium, cobalt, vanadium, manganese, graphite, nickel, zinc and copper) The extraction of most critical raw materials is still in the exploration phase Well-developed infrastructure and expertise in mining with much focus on sustainability	LKAB Boliden Talga Resources Leading Edge Materials Eurobattery Minerals
Active materials	Increasing initiatives on production of active materials Investment in R&D of cathode active materials	Northvolt Graphmatec Bright Day Graphene Altris Dongjin Sweden
Cell production	Currently in a construction phase (Northvolt) Through vertical integration, Northvolt has several parts of the battery value chain integrated into the company. New startups investing in new innovative types of battery model	NILAR (nickel batteries) SAFT (lead batteries) Startups: Enerpoly, Rivus
Pack production	Major users of Li-ion batteries (e.g. automotive) bring the development and manufacturing of battery packs in house to enable optimal integration with tools or vehicles There are players who manufacture battery packs for other end-users such as for energy storage and for industrial vehicles	Epiroc Scania Volvo AB and Volvo Cars Polarium Alelion
Use	Automotive companies clearly set the goals towards electrified fleets resulting in the increasing need for Li-ion batteries Other sectors: mining, autonomous logistics solutions, industrial solutions and portable household tools.	Scania, Volvo AB, Volvo Cars Epiroc and Sandvik Einride ABB and Nortical Husqvarna
Integration	Partnership between battery producer (Northvolt) and energy provider (Vattenfall) for portable energy storage Collaborative project to test the possibilities with batteries in the electricity grid Increasing number of charging projects	Northvolt and Vattenfall Mälarenergi and Northvolt ABB Ferroamp
Recycling	Several major investments from business in recycling (e.g. Revolt Ett) Increasing number of R&D projects Plans to establish a complete system for battery recycling	Stena recycling BatteryLoop Northvolt

EV battery value chain in Sweden.

Despite the still low volume, the EOL LIBs in Sweden are currently collected, pre-processed by Swedish company El-Kretsen, one of Sweden's nationally approved collection system for waste electrical and electronic equipment (WEEE) and batteries (Samarukha, 2020). El-Kretsen offers a collection solution for the new generation of EV batteries, but car manufacturers and those who collect batteries from EVs can also have agreements directly with recyclers. Collected lithium and lithium-ion batteries are transported from Sweden to facilities in Europe (El-Kretsen, n.d.), for instance, to a Finnish battery recycling company, Akkuser Oy, which also receives EOL batteries from several other countries in Europe. In the future, it is expected that there will be an increase in local LIB recycling capacity as a response to market demand while aiming to establish a more resilient supply chains for batteries materials. Stena Recycling is investing in building a recycling plant with an annual capacity of 10,000 tonnes. Northvolt also will increase its recycling capacity by five times to an annual capacity of 125, 000 tonnes.

Today, recyclers mainly target metals in the cathode, such as cobalt and nickel, with high prices, while recovery of lithium and graphite are not yet economically efficient. The spent graphite is technically feasible to be recycled and reused in the LIBs to alleviate the shortage of natural graphite resources and the negative environmental impact of not disposing of them properly. Synthetic graphite is widely used and mainly supplied by China. However, the production of synthetic graphite is highly energy-intensive and combined with coal-dominated China's energy mix resulting in a material with a high carbon footprint. Bio-based carbon materials can be possible replacements for graphite, and are receiving more attention as a renewable alternative.

There is a growing number of R&D and pilot projects involving EV manufacturers and power equipment companies to see second-life battery storage as a way to bring down the capital costs of commercial- and grid-scale battery installations. Repurposing EV batteries for ESS could result in environmental and economic benefits, such as emission and cost reduction in grid systems while providing flexible services It generates added benefits of extending battery life, lessening demand for new batteries in ESS (Ai et al., 2019), provides up to 56% reduction in CO_2 emissions over the total lifecycle of batteries (Ahmadi et al., 2014) and could improve substantially the efficiency of electric grids by shifting power from peak to off-peak demand times (Aziz et al., 2015; Huda et al., 2020). It can also help in reducing the hazards due to landfill disposal and decrease the lifecycle impacts of EV batteries. However, several challenges in the EOL management of EV batteries must be addressed to tap this new pool of battery supply.

In the year 2030, around 14,000 EV batteries are expected to be at their EOL in Sweden. This number could rise significantly to 0.4 million in the year 2050. Compared to the number of EOL EV battery volumes in the EU, which could reach approximately 3 million EV batteries in the year 2040 (Abdelbaky et al., 2021), the EOL markets in Sweden are relatively small. However, EV battery value chain does not isolated at the national level, but it is entrenched on a regional and global level through international trade and resource flows. Thus, it is also crucial to understand the transition to CE from a wider spatial scales i.e. global perspective.

4.2. Enabling circularity of EV batteries

A range of strategies can be adopted to effectively reduce demand for new battery materials in EV, in line with the circular economy approach. However, as have been widely discussed in the literature, a number of key issues related to technical, economical, institutional and political aspects along the battery value chains should be addressed. This subsection briefly discusses the enabling factors for creating a circular battery value chain.

To establish a closed-loop supply chain, there is a lack of established and effective return flow of electric vehicle batteries, which creates an urgency to develop efficient collection networks (Prevolnik and Ziemba, 2019). Current established recycling networks for lead-acid batteries are not designed for handling and processing high volumes of the technically complex, divergent Li-batteries. Supply chain traceability is thus essential to enable closed-loop supply chains. It facilitates capturing, sharing, and managing the crucial EV batteries information amongst the actors during production, use, and reuse/recycle phases (See Fig. A10 in the Supplementary Material). The battery management system (BMS) can be configured to have appropriate features to ensure traceability data gathering and sharing in EV batteries. Nevertheless, the extent of traceability data capturing and sharing depends on the type of circular economy model. For instance, the traceability data recording would be much lesser if the supply chain, including the reverse flow, is fairly controlled by the focal firm and consist of limited trustable partners. In such supply chains, the possibility of material leakage is low as the product returns to same actors for refurbishing or recycling. Contrary to this, the provenance of products with appropriate data capturing and sharing becomes very significant in a supply chain with multiple partners having low trust. Further, supply chain traceability can make sure that the captured information is correct, thus would facilitate variety of reuse of EV batteries possibility of multiple ownership transfer.

The transportation and logistics of EV batteries have been identified as one of the key issues (Dominish et al., 2021). With the sharp increase in volume and still underdeveloped infrastructure, LIB may be either landfilled or temporarily stored leading to environmental risk such as pollutants and contaminants release and accidental fires (Mrozik et al., 2021). The safety, cost, and regulatory considerations of transporting and storing batteries would be a valuable area for future study, as would further exploration of actors involved in the EV battery value chain.

The hazardous nature of EV batteries is further complicated because different manufacturers use different battery chemistries and their packs come in a range of different shapes, sizes, and disassembly requirements. Designers and manufacturers should improve the design for easier disassembly and recycling battery (Rajaeifar et al., 2022). Whilst the standardisation of design practices and configurations for EV batteries can be a part of the solution here, issues of intellectual property may make this solution impractical. At the very least, improved standards around the labelling of batteries would be of benefit. Traceability, in this direction, facilitates recalling the history of EV batteries, including the composition of EV batteries raw material - grade of product and its origin, which is also crucial to enable appropriate reuse and recycling of the EV batteries. Some incentives to ensure those processing batteries for recycling and second-life applications having adequate information about the battery would encourage the new market development.

Currently, no definition or standards for reuse or repurposing in the Batteries Directive creates legal uncertainty concerning those activities. Improved standards are required related to methods to evaluate battery safety and performance for second-life applications and standards for battery reuse, refurbishment, and repurpose requirements.

The current policy landscape for batteries in Sweden relies on EU legislation. At the national level, the Swedish strategy for a sustainable battery value chain shows action plans to contribute to the European battery industry. The EU is preparing stricter battery regulations, which are expected to come into force in 2022–2023, to secure the sustainability and competitiveness of battery value chains. The proposal includes measures to introduce product carbon footprint rules, material-specific recycling targets, minimum recycled content, a 'battery passport', and reinforce the due diligence of supply chains (European Commission, 2020), which would have a wide-ranging influence on the entire battery value chain in Sweden, EU and globally. On the one hand, the new battery regulation will provide legal certainty that can facilitate investments and innovations in sustainable battery production, exerting the pressure on the battery manufacturers to comply with supply chain transparency and to achieve targets on carbon footprint and recycled content in the batteries (Melin et al., 2021). The proposal also defines a framework which will facilitate the repurposing of batteries from EVs and introduce battery passports so that the recycling and reuse can be monitored, thus reinforcing the creation of a new market for second life technology.

While the new regulation provides required policies that address environmental and social issues, Melin et al. (2021) pointed out that the new legislation may bring unintended consequences such as imbalance between new and mature markets (i.e. China and South Korea) by directly or in directly giving firms that manage to comply competitive benefits. Further, highly stringent regulations on batteries may risk hampering competitiveness related to associate compliance costs, leading to decreased innovation and lower EV adoption rates. Additionally, the material-specific recycling target and recycled content might become obsolete, due to technological advances where other materials may become relevant in the future. This issue has been raised by battery makers in Sweden and EU highlighting that overly demanding requirements may risk hamper investments, reduce flexibility and create obstacles to the important transition to climate neutrality (EUROBAT, 2020; Swedish Enterprise, 2021). All in all, despite a better outlook on the circular EV battery value chain in Sweden and Europe, more needs to be done in order to provide a more stable and predictable framework to foster investments in this industry.

5. Conclusions

This study forecasts the future waste volume and demand for batteries in the Swedish passenger EV fleet and the potential contribution of EV battery recycling and reuse in achieving a future circular battery economy. As sales of EVs grow, the demand for EVB materials will rapidly increase towards 2030, yet can be substantially reduced through recycling, reuse and advances in battery technology. The quantity of EV batteries used in Swedish passenger vehicles is expected to increase around ten-fold in the next decade and may reach 28–60 GWh by 2050, depending on the scenarios. Achieving high rates of recycling can significantly support the supply of battery materials, highlighting the needs and opportunities to build and expand recycling plant capacity. The study also illustrates how different timings for ICE ban have a substantial impact on material flow and net demand for primary LIB materials. Policy intervention is needed to promote effective recycling, such as improved collection systems, better traceability over battery lifetimes and standardisation in the design, transport, handling and recycling of EV batteries. Further support to R&D and industrial-scale innovation activities is also essential in developing cost-effective recycling technologies, mainly on materials that are currently not recycled or less valuable, such as lithium and graphite.

Innovative business models such as produce-service systems can be drivers of the CE transition of EV batteries. This however entails new policies that encourage increased liability and traceability and create favourable market conditions for the emergence of new business models as well as enabling regulatory framework to facilitate further commercial deployment of second battery life technologies. This strategy also provides integration possibilities with ESS. On the other hand, while recycling and reuse are crucial strategies, policy should also focus on reducing demand for new batteries through fostering greater adoption of shared mobility practices and public transport.

Transition research is concerned with long-term processes of radical and systemic change involving fundamental social, technical, institutional, policy, economic and/or environmental processes. Incorporating a socio-technical transition perspective into scenario-driven MFA can shed some light on the dynamics of transitions in socio-technical systems, particularly how transition processes on different levels might contribute to a CE of EV battery. The combination of MFA and transition research enables both the material and the social dimension of the transformative processes into resource efficient economies. Whilst this paper focuses on Sweden, it should be noted that the transition processes are a part of a global resource economy. This highlights the importance of enabling international collaboration and the development of global governance frameworks to support circular EV battery value chains at scale. In Sweden's context, for instance, the Nordic collaboration can offer stronger value propositions with regards to attracting investments and partnerships within the battery value chain.

Developing quantitative scenarios that span long time horizons of several decades is fraught with high uncertainties related to market dynamics, battery and EV lifespan, the development of battery technologies, and future policy framework. Although a number of uncertainties exist, the estimation can give a useful indication of the magnitude of the potential impacts when changing the scenario parameters. Further, the increasing trend in EV adoption will definitely have impacts on the electricity market in the country, and associated materials will be needed for capacity improvement in the sector. However, the material flow impacts of such changes have not been studied in the literature, which calls for future research. More in-depth sustainability assessment and complementary transition studies exploring societal implications of CE of EV batteries will be necessary to support national and EU policy development. Given the importance of traceability to facilitate effective reuse/recycling of EV batteries, understanding actor dynamics and identifying ways to incentivize supply chain partners and the end user to promote information sharing are worth to be explored. This research and future research can contribute to giving more insights and an evidence base in establishing a roadmap towards a circular battery value chain.

CRediT authorship contribution statement

Anissa Nurdiawati: Conceptualization, Methodology, Investigation, Formal analysis, Software, Validation, Writing – original draft, Writing – review & editing. **Tarun Kumar Agrawal:** Investigation, Visualization, Writing – review & editing.

Declaration of Competing Interest

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Supplementary materials

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References

Abdelbaky, M., Peeters, J.R., Dewulf, W., 2021. On the influence of second use, future battery technologies, and battery lifetime on the maximum recycled content of future electric vehicle batteries in Europe. Waste Manag. 125, 1–9. https://doi.org/10.1016/j.wasman.2021.02.032.

Ahmadi, L., Yip, A., Fowler, M., Young, S.B., Fraser, R.A., 2014. Environmental feasibility of re-use of electric vehicle batteries. Sustain. Energy Technol. Assess. 6, 64–74. https://doi.org/10.1016/j.seta.2014.01.006.

Ai, N., Zheng, J., Chen, W.Q., 2019. U.S. end-of-life electric vehicle batteries dynamic inventory modeling and spatial analysis for regional solutions. Resour. Conserv. Recycl. 145, 208–219. https://doi.org/10.1016/j.resconrec.2019.01.021.

Andersson, M., Söderman, M.L., Sandén, B.A., 2019. Adoption of systemic and socio-technical perspectives in waste management, WEEE and ELV research. Sustain 11. https://doi.org/10.3390/su11061677.

Aziz, M., Oda, T., Mitani, T., Watanabe, Y., 2015. T Kashiwagi.Utilization of electric vehicles and their used batteries for peak-load shifting. Energies 8 (5), 3720–3738.

BIL Sweden, 2021. Tidsserier nyregistreringsstatistik (Time series new registration statistics) [WWW Document]. URL https://www.bilsweden.se/statistik/Tidsserier/ (accessed 9.1.21).
Baars, J., Domenech, T., Bleischwitz, R., Melin, H.E., Heidrich, O., 2021. Circular economy strategies for electric vehicle batteries reduce reliance on raw materials. Nat. Sustain. 4, 71–79. https://doi.org/10.1038/s41893-020-00607-0.
Banza Lubaba Nkulu, C., Casas, L., Haufroid, V., De Putter, T., Saenen, N.D., Kayembe-Kitenge, T., Musa Obadia, P., Kyanika Wa Mukoma, D., Lunda Ilunga, J.M., Nawrot, T.S., Luboya Numbi, O., Smolders, E., Nemery, B., 2018. Sustainability of artisanal mining of cobalt in DR Congo. Nat. Sustain. 1, 495–504. https://doi.org/10.1038/s41893-018-0139-4.
Bidmon, C.M., Knab, S.F., 2018. The three roles of business models in societal transitions new linkages between business model and transition research. J. Clean. Prod. 178, 903–916. https://doi.org/10.1016/j.jclepro.2017.12.198.
Business Sweden, 2021. Den Nordiska Batterivärdekedjan (The Nordic battery Value Chain). Stockholm, Sweden.
Cano, Z.P., Banham, D., Ye, S., Hintennach, A., Lu, J., Fowler, M., Chen, Z., 2018. Batteries and fuel cells for emerging electric vehicle markets. Nat. Energy 3, 279–289. https://doi.org/10.1038/s41560-018-0108-1.
Casals, L.C., Amante García, B., Canal, C., 2019. Second life batteries lifespan rest of useful life and environmental analysis. J. Environ. Manage. 232, 354–363. https://doi.org/10.1016/j.jenvman.2018.11.046.
Chizaryfard, A., Nuur, C., Trucco, P., 2022. Managing structural tensions in the transition to the circular economy the case of electric vehicle batteries. Circ. Econ. Sustain. 10.1007/s43615-022-00152-2.
Dahllöf, L., Romare, M., Wu, A., 2019. Mapping of lithium-ion batteries for vehicles a study of their fate in the nordic countries, lithium-ion batteries. 10.1201/9780429259340.
Ding, Y., Cano, Z.P., Yu, A., Lu, J., Chen, Z., 2019. Automotive Li-ion batteries current status and future perspectives. Electrochem. Energy Rev. 2, 1–28. https://doi.org/10.1007/s41918-018-0022-z.
Dominish, E., Florin, N., 2021. Reducing New Mining For Electric Vehicle Battery metals Responsible Sourcing Through Demand Reduction Strategies and Recycling. NSW.
Duarte Castro, F., Cutaia, L., Vaccari, M., 2021. End-of-life automotive lithium-ion batteries (LIBs) in Brazil prediction of flows and revenues by 2030. Resour. Conserv. Recycl. 169 https://doi.org/10.1016/j.resconrec.2021.105522.
EUROBAT, 2020. Position Paper On the Proposal For a New Batteries Regulation.
Ellen MacArthur Foundation, 2017. Circular Economy in detail [WWW Document]. 10.7765/9781526145178.00007.
European Commission, 2016. SET - Plan ACTION – Declaration of Intent “Become competitive in the Global Battery Sector to Drive E-Mobility forward.” Brussels, Belgium.
European Commission, 2020. Proposal For a Regulation of the European Parliament and of the Council concerning Batteries and Waste batteries, repealing. Directive 2006/66/EC and Amending Regulation (EU) No 2019/1020. Brussels, Belgium.
Fallah, N., Fitzpatrick, C., Killian, S., Johnson, M., 2021. End-of-life electric vehicle battery stock estimation in ireland through integrated energy and circular economy modelling. Resour. Conserv. Recycl. 174, 105753 https://doi.org/10.1016/j.resconrec.2021.105753.
Fossil Free Sweden, 2020. Strategy for fossil free competitiveness - sustainable battery value chain.
Geels, F.W., Schot, J., 2007. Typology of sociotechnical transition pathways. Res. Policy 36, 399–417. https://doi.org/10.1016/j.respol.2007.01.003.
Geels, F.W., Kern, F., Fuchs, G., Hinderer, N., Kungl, G., Mylan, J., Neukirch, M., Wassermann, S., 2016. The enactment of socio-technical transition pathways a reformulated typology and a comparative multi-level analysis of the German and UK low-carbon electricity transitions (1990-2014). Res. Policy 45, 896–913. https://doi.org/10.1016/j.respol.2016.01.015.
Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes a multi-level perspective and a case-study. Res. Policy 31, 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8.
Geels, F.W., 2011. The multi-level perspective on sustainability transitions responses to seven criticisms. Environ. Innov. Soc. Trans. 1, 24–40. https://doi.org/10.1016/j.eist.2011.02.002.
Government Offices of Sweden, 2018. The Swedish climate policy framework.
Halleux, V., 2021. New EU regulatory framework for batteries - Setting sustainability requirements.
Hossain, E., Murtaugh, D., Mody, J., Faruque, H.M.R., Sunny, M.S.H., Mohammad, N., 2019. A comprehensive review on second-life batteries current state, manufacturing considerations, applications, impacts, barriers potential solutions, business strategies, and policies. IEEE Access 7, 73215–73252. https://doi.org/10.1109/ACCESS.2019.2917859.
Huda, M., Koji, T., 2020. Techno economic analysis of vehicle to grid (V2G) integration as distributed energy resources in Indonesia power system. Energies 13, 1162.
IEA, 2018a. Nordic EV Outlook 2018. Nordic EV Outlook, p. 2018.
IEA, 2018b. Global EV Outlook 2018 Towards Cross-Modal Electrification. Paris, France.
IEA, 2019. Global EV Outlook 2019 Scaling-up the Transition to Electric Mobility. Paris, France.
IEA, 2020. Global EV Outlook 2020. Paris, France.
IEA, 2021. Global EV Outlook 2021 - Accelerating ambitions Despite the Pandemic. Global EV Outlook, p. 2021.
Jedelhauser, M., Mehr, J., Binder, C.R., 2018. Transition of the Swiss Phosphorus system towards a circular economy-Part 2 socio-technical scenarios. Sustain 10. https://doi.org/10.3390/su10061980.
Jena, K.K., Alfantazi, A., Mayyas, A.T., 2021. Comprehensive review on concept and recycling evolution of lithium-ion batteries (LIBs). Energy Fuels 35, 18257–18284. https://doi.org/10.1021/acs.energyfuels.1c02489.
Kamran, M., Raugei, M., Hutchinson, A., 2021. A dynamic material flow analysis of lithium-ion battery metals for electric vehicles and grid storage in the UK assessing the impact of shared mobility and end-of-life strategies. Resour. Conserv. Recycl. 167, 105412 https://doi.org/10.1016/j.resconrec.2021.105412.
Kelly, J.C., Dai, Q., Wang, M., 2019. Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries. Mitig. Adapt. Strateg. Glob. Chang. 371–396. https://doi.org/10.1007/s11027-019-09869-2.
Lauttamäki, V., Hyysalo, S., 2019. Empirical application of the multi-level perspective tracing the history of ground-source heat pumps systems in Finland. Sustain. Sci. Pract. Policy 15, 82–103. https://doi.org/10.1080/15487733.2019.1678372.
Liu, Wenqiu, Liu, Wei, Li, X., Liu, Y., Ogunmoroti, A.E., Li, M., Bi, M., Cui, Z., 2021. Dynamic material flow analysis of critical metals for lithium-ion battery system in China from 2000 to 2018. Resour. Conserv. Recycl. 164, 105122 https://doi.org/10.1016/j.resconrec.2020.105122.
Lunde, P., 2021. Facilitating Circularity in the Lithium-ion Battery Value Chain By Designing for Recycling. Chalmers University of Technology.
Melin, H.E., Rajaeifar, M.A., Ku, A.Y., Kendall, A., Harper, G., Heidrich, O., 2021. Global implications of the EU battery regulation. Science (80-.) 373, 384–387. https://doi.org/10.1126/science.abh1416.
Melin, H.E., 2019. State of the art in reuse and recycling of lithium-ion batteries-a research review. Circ. Energy Storage 1, 1–57.
Moradi, B., Botte, G.G., 2016. Recycling of graphite anodes for the next generation of lithium ion batteries. J. Appl. Electrochem. 46, 123–148. https://doi.org/10.1007/s10800-015-0914-0.
Morfeldt, J., Davidsson Kurland, S., Johansson, D.J.A., 2021. Carbon footprint impacts of banning cars with internal combustion engines. Transp. Res. Part D Transp. Environ. 95, 102807 https://doi.org/10.1016/j.trd.2021.102807.
Mrozik, W., Rajaeifar, M.A., Heidrich, O., Christensen, P., 2021. Environmental impacts, pollution sources and pathways of spent lithium-ion batteries. Energy Environ. Sci. 14, 6099–6121. https://doi.org/10.1039/d1ee00691f.
Naturvårdsverket, 2020. Extended Producer Responsibility in Sweden.
Neubauer, J., Smith, K., Wood, E., Pesaran, A., 2015. Identifying and overcoming critical barriers to widespread second use of PEV batteries. Natl. Renew. Energy Lab. 23–62.
Prevolnik, F., Ziemba, A., 2019. The reverse logistics of electric vehicle batteries Challenges encountered by 3PLs and recyclers.
Rajaeifar, M.A., Ghadimi, P., Raugei, M., Wu, Y., Heidrich, O., 2022. Challenges and recent developments in supply and value chains of electric vehicle batteries a sustainability perspective. Resour. Conserv. Recycl. 180 https://doi.org/10.1016/j.resconrec.2021.106144.
Richa, K., Babbitt, C.W., Gaustad, G., Wang, X., 2014. A future perspective on lithium-ion battery waste flows from electric vehicles. Resour. Conserv. Recycl. 83, 63–76. https://doi.org/10.1016/j.resconrec.2013.11.008.
Rip, A., Kemp, 1998. Technological Change. In: Rayner, S., Malone, E.L. (Eds.), Human Choice and Climate Change Vol. II, Resources and Technology. Battelle Press, pp. 327–399. https://doi.org/10.1016/B978-008044910-4.00230-3.
Salmenperä, H., 2021. Different pathways to a recycling society – comparison of the transitions in Austria, Sweden and Finland. J. Clean. Prod. 292 https://doi.org/10.1016/j.jclepro.2021.125986.
Samarukha, I., 2020. Recycling strategies for End-of-Life Li-ion Batteries from Heavy Electric Vehicles 1–52.
Schwich, L., Sabarny, P., Friedrich, B., 2020. Recycling potential of lithium–sulfur batteries— a first concept using thermal and hydrometallurgical methods. Metals (Basel) 10, 1–19. https://doi.org/10.3390/met10111513.
Shafique, M., Rafiq, M., Azam, A., Luo, X., 2022. Material flow analysis for end-of-life lithium-ion batteries from battery electric vehicles in the USA and China. Resour. Conserv. Recycl. 178, 106061 https://doi.org/10.1016/j.resconrec.2021.106061.
Swedish Enterprise, 2021. The Confederation of Swedish Enterprise Consultation response. The Battery Regulation.
Swedish Transport Administration, 2019. Analysis of Road Safety Trends 2018. Borlänge. Sweden.
Tadaros, M., Migdalas, A., Samuelsson, B., Segerstedt, A., 2022. Location of facilities and network design for reverse logistics of lithium-ion batteries in Sweden. Oper. Res. 22, 895–915. https://doi.org/10.1007/s12351-020-00586-2.
Tan, P., Jiang, H.R., Zhu, X.B., An, L., Jung, C.Y., Wu, M.C., Shi, L., Shyy, W., Zhao, T.S., 2017. Advances and challenges in lithium-air batteries. Appl. Energy 204, 780–806. https://doi.org/10.1016/j.apenergy.2017.07.054.
The Advanced Rechargeable & Lithium Batteries Association, 2018. PEFCR - product environmental footprint category rules for high specific energy rechargeable batteries for mobile applications.
Thorne, R., Aguilar Lopez, F., Figenbaum, E., Fridstrøm, L., Müller, D.B., 2021. Estimating stocks and flows of electric passenger vehicle batteries in the Norwegian fleet from 2011 to 2030. J. Ind. Ecol. 2025, 1–14. https://doi.org/10.1111/jiec.13186.
Transport Analysis, 2021. Körsträckor med svenskregistrerade fordon (Mileage for vehicles registered in Sweden) [WWW Document]. URL https//www.trafa.se/vagtrafik/korstrackor/(accessed 9.1.21).
Tsiropoulos, I., Tarvydas, D., Lebedeva, N., 2018. Li-ion Batteries For Mobility and Stationary Storage Applications - Scenarios for Costs and Market Growth. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/8717.
van den Brink, S., Kleijn, R., Sprecher, B., Tukker, A., 2020. Identifying supply risks by mapping the cobalt supply chain. Resour. Conserv. Recycl. 156, 104743 https://doi.org/10.1016/j.resconrec.2020.104743.

Verbong, G.P.J., Geels, F.W., 2010. Exploring sustainability transitions in the electricity sector with socio-technical pathways. Technol. Forecast. Soc. Change 77, 1214–1221. https://doi.org/10.1016/j.techfore.2010.04.008.

Williams, A., 2007. Product service systems in the automobile industry contribution to system innovation. J. Clean. Prod. 15, 1093–1103. https://doi.org/10.1016/j.jclepro.2006.05.034.

Xu, C., Dai, Q., Gaines, L., Hu, M., Tukker, A., Steubing, B., 2020. Future material demand for automotive lithium-based batteries. Commun. Mater. 1, 99. https://doi.org/10.1038/s43246-020-00095-x.

Yang, X., Torppa, A., Kärenlampi, K., 2021. Evaluation of graphite and metals separation by flotation in recycling of Li-ion batteries 30. 10.3390/materproc2021005030.